Steady Inductive Helicity Injection on a High Beta Spheromak, T. R. Jarboe and P. Sieck

Abstract

This concept is to develop a new steady inductive helicity injection (SIHI) current drive method that can be used to form and sustain high-beta spheromaks, spherical tori (STs), and reversed field pinches (RFPs). In a reactor, helicity injection current drive promises to be orders of magnitude more efficient than neutral beam and rf current drive. While desirable in a tokamak, this improvement is essential for spheromaks and RFPs with lower β-poloidal (requiring more current) and lower q (giving less bootstrap current). Two injectors, oscillating out of phase, produce a constant helicity injection rate.

The first application is to a high beta spheromak with potential major advancements in the development of helicity injection current drive and the spheromak reactor concept. SIHI maintains a constant optimal high β current profile through constant injection with no energy or helicity ejection. Other AC helicity injection methods have helicity and energy ejection during part of the cycle, which causes plasma flow into the wall. The ejection phase can also change the current profile from optimal, leading to more plasma loss to the wall. The equilibrium is in a close fitting flux conserver with no field lines penetrating the walls. Both the spheromak and RFP require a nearby conducting wall for stability. Open field lines act as helicity sinks and have been shown to degrade the performance of RFPs and

spheromaks. SIHI is compatible with the shape and gives the current profile needed for a high β spheromak. The optimal spheromak shape has a “bow tie” cross section with a very short plasma length on the geometric axis. This results in a very short current path for coaxial helicity injection (CHI) that might cause serious arcing problems. SIHI does not apply an axial voltage. SIHI produces the hollow current profile needed for high β in both the spheromak and the ST. The higher β geometry and improved impurity and density control made possible by SIHI can improve the confinement of the spheromak by orders of magnitude. On HIT, transformer driven discharges with a profusion of relaxation activity require orders of magnitude less power then similar CHI discharges, indicating that electrodes not relaxation may be deleterious. With the improved confinement and β, in its simple geometry, the spheromak makes an extremely attractive fusion reactor.

With SIHI, helicity is injected with mostly $n = 1$ symmetry and a rotating $n = 1$ magnetic structure is produced. Producing spheromaks using this symmetry of injection was demonstrated at Los Alamos. Such a rotating structure is produced with CHI on spheromak and ST current drive experiments and is thought to be necessary for current drive in the closed flux regions. Driving this structure directly will be more efficient then generating it through instability. Studying relaxation with SIHI will be more conclusive because the injector symmetry and frequency differs from the equilibrium.

Goals

- Constant inductive helicity injection (max β)
- Never eject helicity or power (PMI)
- Sustain spheromak with $\beta \geq 10\%$

$$dK_{inj} / dt = 2 V_{inj} \psi_{inj} \quad (\langle V_{inj} \rangle = 0)$$

Solutions

- Two injectors
- Injector flux reverses
- Bow tie spheromak

Helicity conservation makes current drive simple:

- Magnetic helicity is the best constant of the motion of magnetic fields in plasma.
- Magnetic activity dissipates energy while conserving helicity, making $j_{||}/B$ more uniform.
- Magnetic activity that lowers $j_{||}$ in one area must raise it in others.

Driving $j_{||}$ high in a convenient location gives current drive throughout the volume.

Equations for helicity injection and flux injection:

- Helicity injection

$$dK/dt = 2\int \mathbf{E}_v \bullet \mathbf{B}_v \, d\mathit{vol} - 2\int \mathbf{E} \bullet \mathbf{B} \, d\mathit{vol}$$

where $\mathbf{E}_v$ and $\mathbf{B}_v$ are the vacuum case with the same flux and **E** parallel boundary conditions as the plasma case.

- Flux injection

$$\mathbf{v} = \mathbf{E} \times \mathbf{B}/B^2$$

The flow of the magnetic field is in the same direction as the power flow. If power flows into the plasma from the insulators the plasma will be kept away from the wall.

SIHI on bow tie geometry should increase confinement:

- Increase β - by the shape
- Increase $\gamma\, (\equiv v_d / v_{th})$- by inductive drive
- Lower Z_{eff} – by inductive drive
- This should increase τ_E by a large factor

Spheromak confinement is observed to increase until a β-limit is reached. Therefore, it is β-limited and:

$$\tau_E = 3\beta\tau_W / 2$$

$$\eta \propto Z_{eff} / T^{3/2}$$

$$\tau_W \propto R^2 / \eta \propto R^2 T^{3/2} / Z_{eff} \quad (R = \text{size})$$

$$\beta \propto nT / B^2$$

$$\gamma \propto v_d / v_{th} \propto j / n / T^{1/2}$$

$$n \propto j / \gamma / T^{1/2}$$

$$\beta \propto (j / \gamma / T^{1/2})(T / B^2) \propto (B / R)(1 / \gamma)(T^{1/2} / B^2) \propto T^{1/2} / (R\gamma B)$$
$$\propto T^{1/2} / (\gamma I)$$

$$T \propto (\beta\gamma I)^2$$

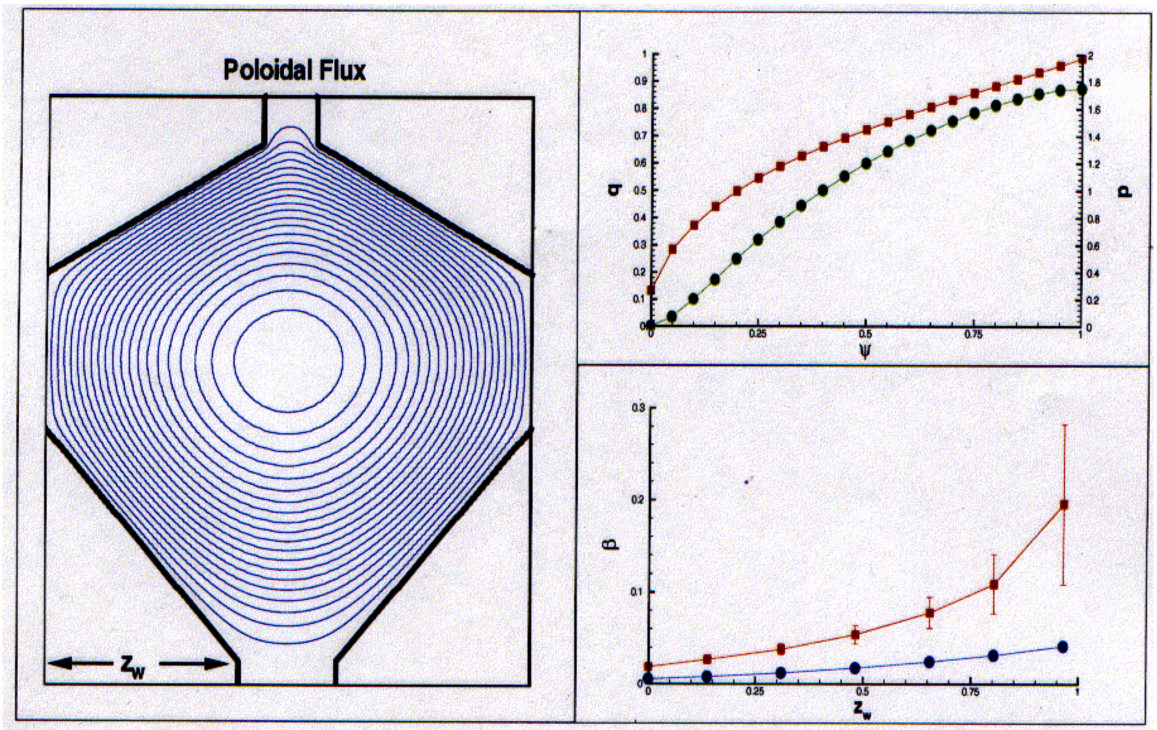
$$\tau_W \propto R^2(\beta\gamma I)^3 / Z_{eff}$$

$$\tau_E \propto \beta^4\gamma^3 I^3 R^2 / Z_{eff}$$

- A factor of two improvement in each of β, γ, and Z_{eff} should increase τ_E by 256.

Mercier β-limit calculations show:

- Bow tie shape gives higher β
- Sustained hollow profile gives higher β than $\lambda(\psi)$ = const.



Z_w

q——

p——

Sustained β——

$\lambda(\psi)$ = const. β——

Steady Inductive Helicity Injection (SIHI) is the only known method of current drive that has all of these features.

- Nearly constant injection rate and current profile
- Optimal high-β current profile
- High power efficiency in a reactor
- Drives n=1 dynamo mode directly
- Inductive method allows density control
- Power and helicity always flow into plasma
- No field lines penetrate walls
- Equilibrium in a close-fitting flux conserver
- Applicable to any toroidal plasma
- Frequency and symmetry not like equilibrium

SIHI improves "AC" helicity injection.

- Other methods oscillate the equilibrium toroidal or poloidal flux by a small amount in phase with an oscillating voltage. Helicity and power are ejected from the plasma when the voltage is negative, leading to plasma wall interaction.

- In this method the voltage is only applied to the injector flux which changes sign with the voltage, allowing helicity and power to always be injected.

- Helicity injection is constant giving a constant-optimum profile. The profile for helicity ejection is greatly different from that of injection

SIHI improves CHI

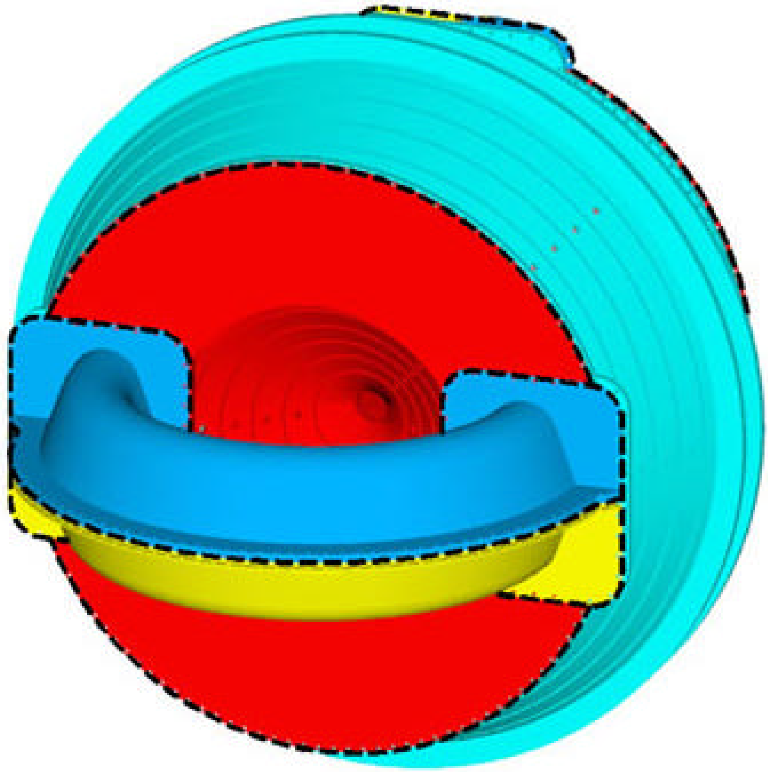
- Better density control: less gas injection required

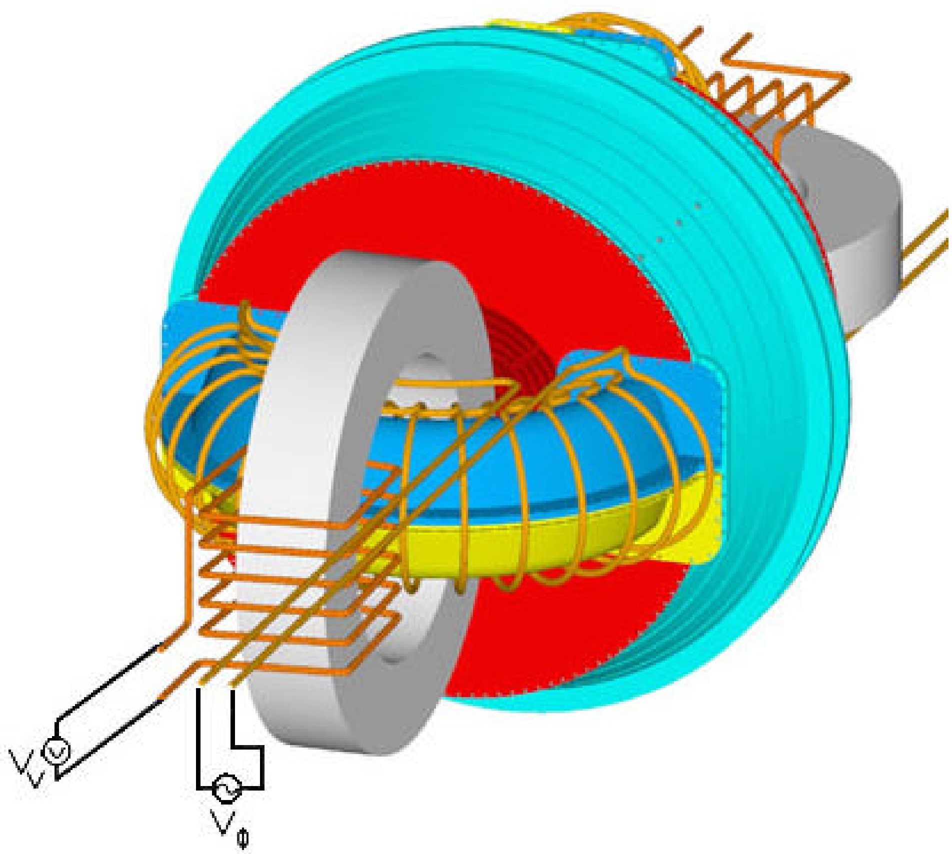
- Cleaner plasma: no impurity generation due to electrode current contact

- Less radiation problems: lower density and cleaner plasma

- Higher efficiency: no high plasma currents required on open field lines. Driven plasma can get hot.

- Transformer drive: less current in the external circuit.



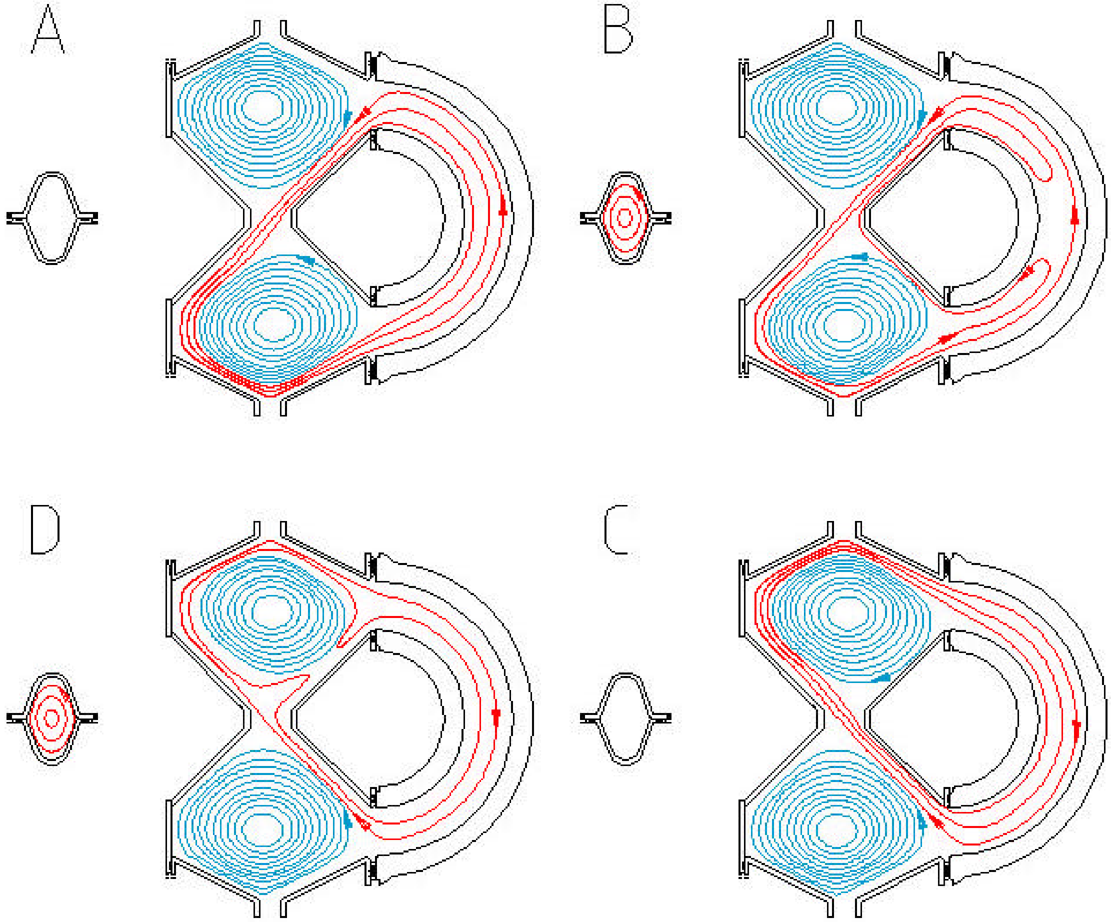

V_V
V_ϕ

Two injectors 90° out of phase give nearly constant helicity injection with a rotating n=1 magnetic structure.

Let $V_{inj} = V_0 \sin \omega t$ and $\psi_{inj} = \psi_0 \sin \omega t$ in one injector.

Let $V_{inj} = V_0 \cos \omega t$ and $\psi_{inj} = \psi_0 \cos \omega t$ in the other injector.

$dK/dt = 2V_0\psi_0 \sin^2 \omega t + 2V_0\psi_0 \cos^2 \omega t = 2V_0\psi_0 = \text{const.}$

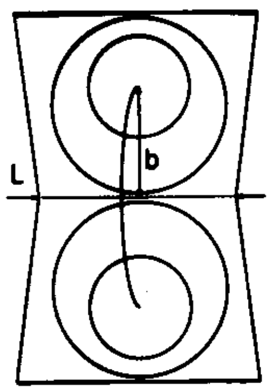


Four times in one half cycle of SIHI showing a 180° rotation of the n=1. Injecting negative flux decreases the flux in the injector.

INCREASING MAGNETIC SHEAR

Cylindrical Flux-Conserver:

- $q(0) = \lambda(0)L/4\pi$ * Lower to raise shear (small L)
- $q(\psi_0) = 2/\lambda(\psi_0)b$ Raise to raise shear (small $\lambda(\psi_0)$)



b = radius at $\psi = \psi_0$
(magnetic axis)

L = length at $\psi = 0$

Modify Flux-Conserver Geometry:

- ~~maintain uniform λ profile~~ Hollow j profile
- shorten L to lower $q(0)$ and increase shear

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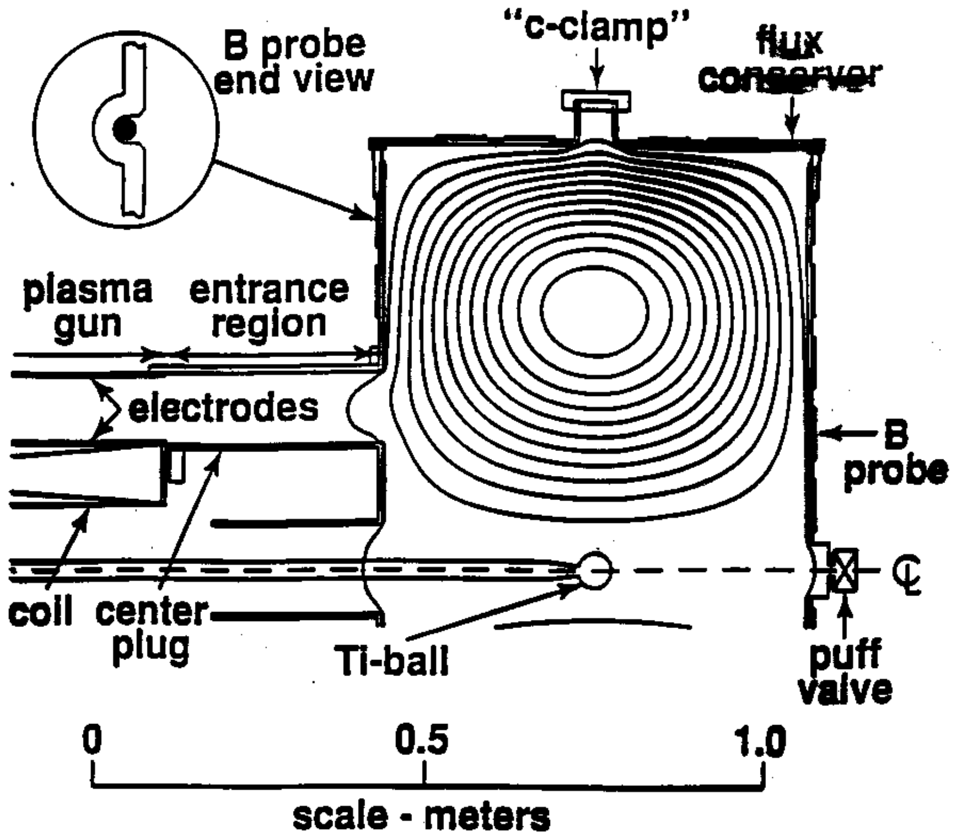
* J. M. Finn, *et al.*, Phys. Fluids **24** (1981) 1336.



1. A spheromak in the CTX low-field-error flux conserver. The entrance region, center plug, and flux conserver are all made from OFHC Cu. The electrodes are W-coated stainless steel. The Ti ball is shown in the position used for coating; it is retracted into the coaxial source for spheromak operation. The equilibrium poloidal flux contours shown were calculated with a typical (small) value of bias flux.

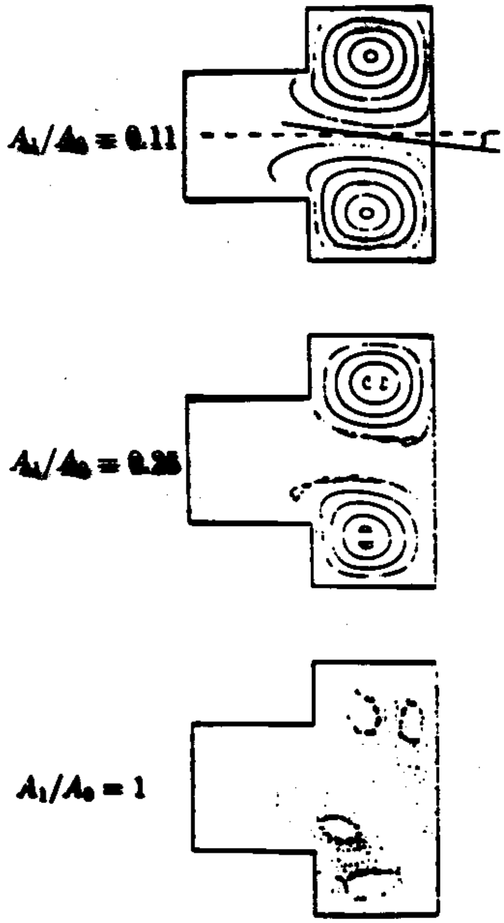
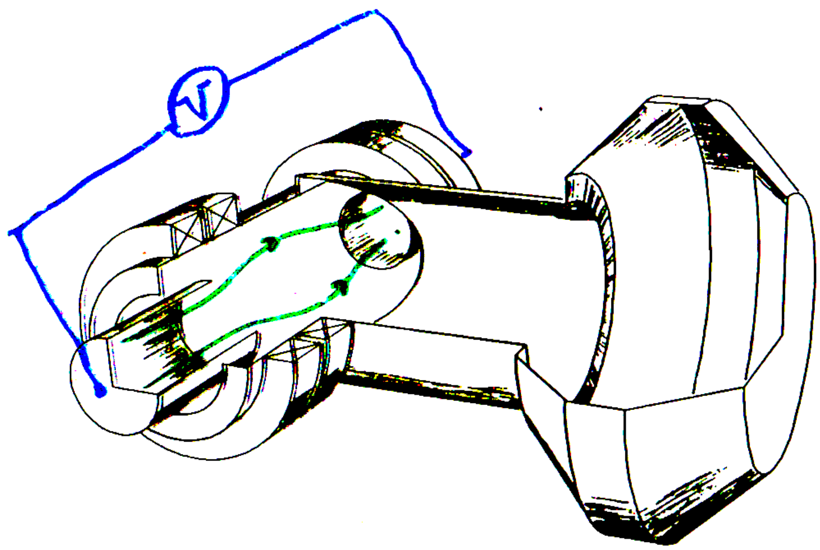


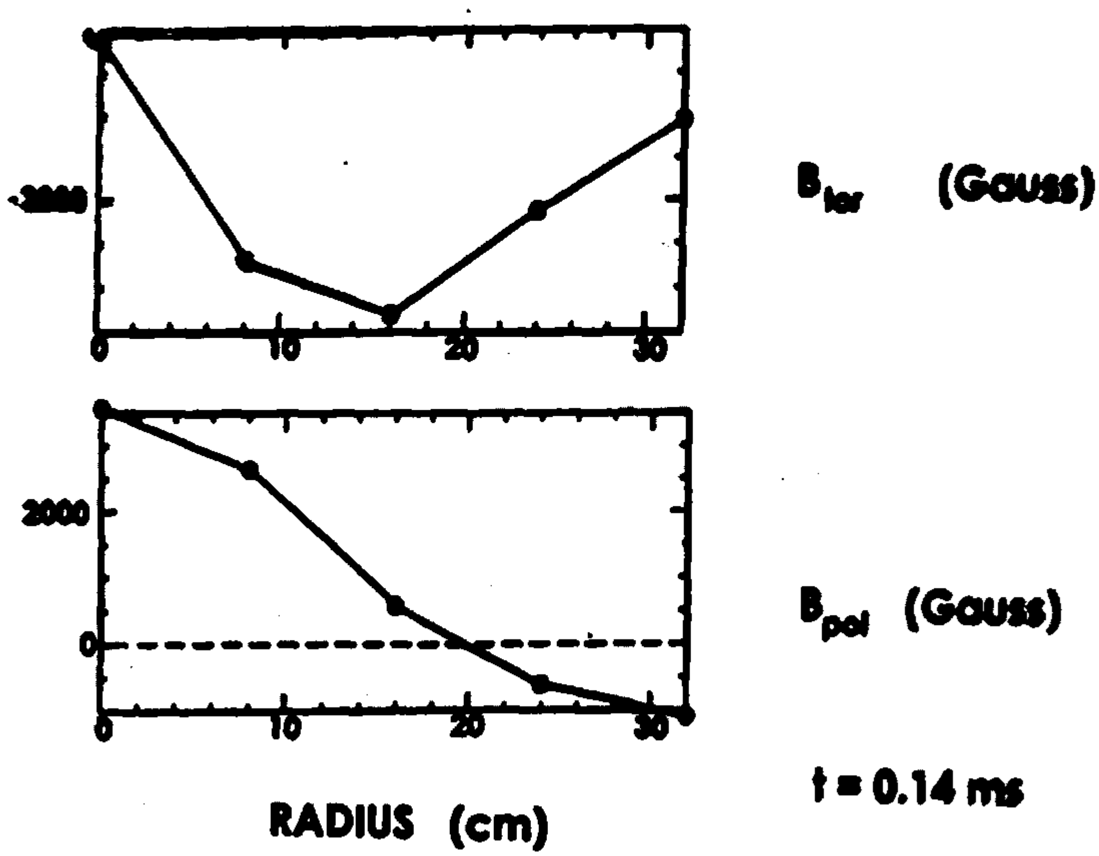
FIG. 3. Magnetic-field line puncture plots for different ratios of A_1 to A_0, where A_n is the amplitude of the nth state. This figure illustrates that significant stochasticity can be induced in the spheromak field lines by the $m = 1$ state.

J.C. Fernandez et al.

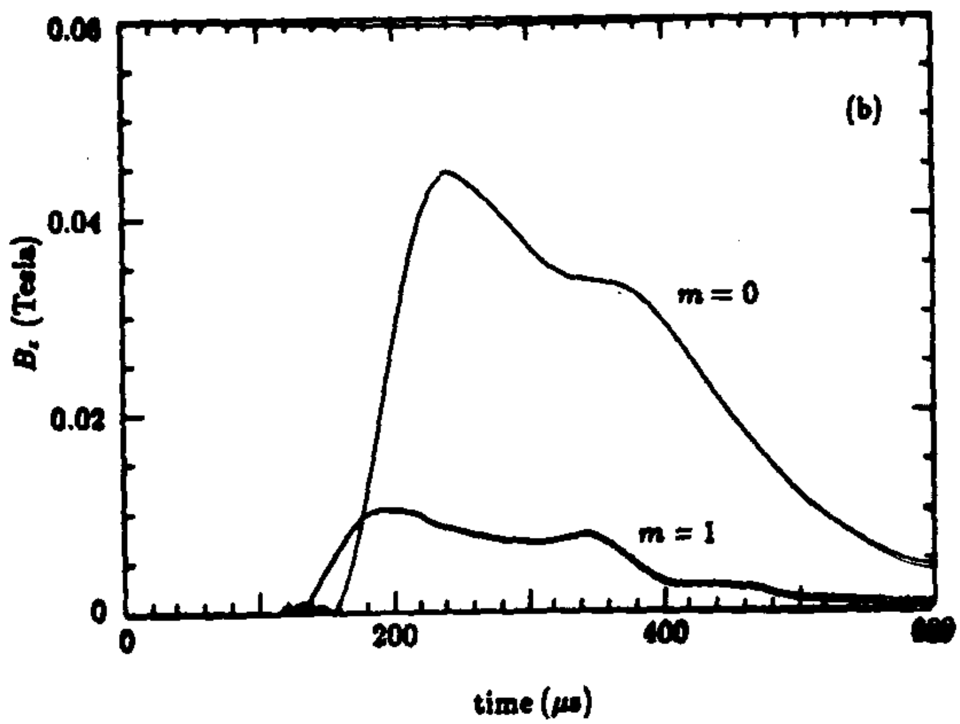


$$\dot{K} = -\frac{K}{\tau_0^2} + 2V\Phi$$

Internal toroidal and poloidal fields in the m=1 spheromak experiment, indicating a mostly axisymmetric equilibrium.



Even in a cold spheromak, the m=1 driving fields do not cause a great deal of open flux.

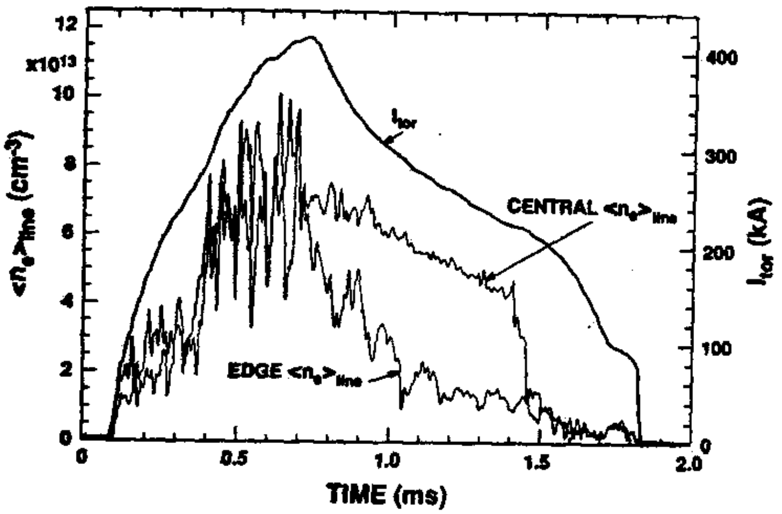


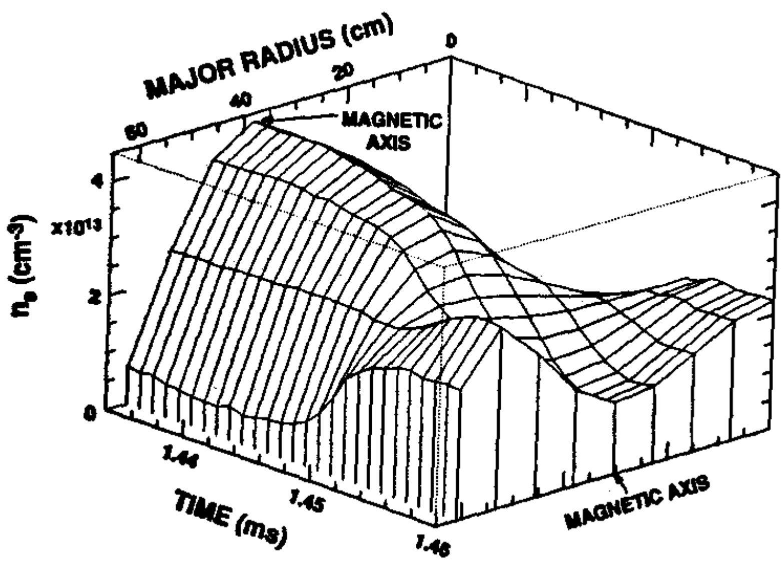
Amplitude of the m=0 (the equilibrium fields) and the m=1 (helicity source fields) vs time for a spheromak produced by the m=1 helicity source.

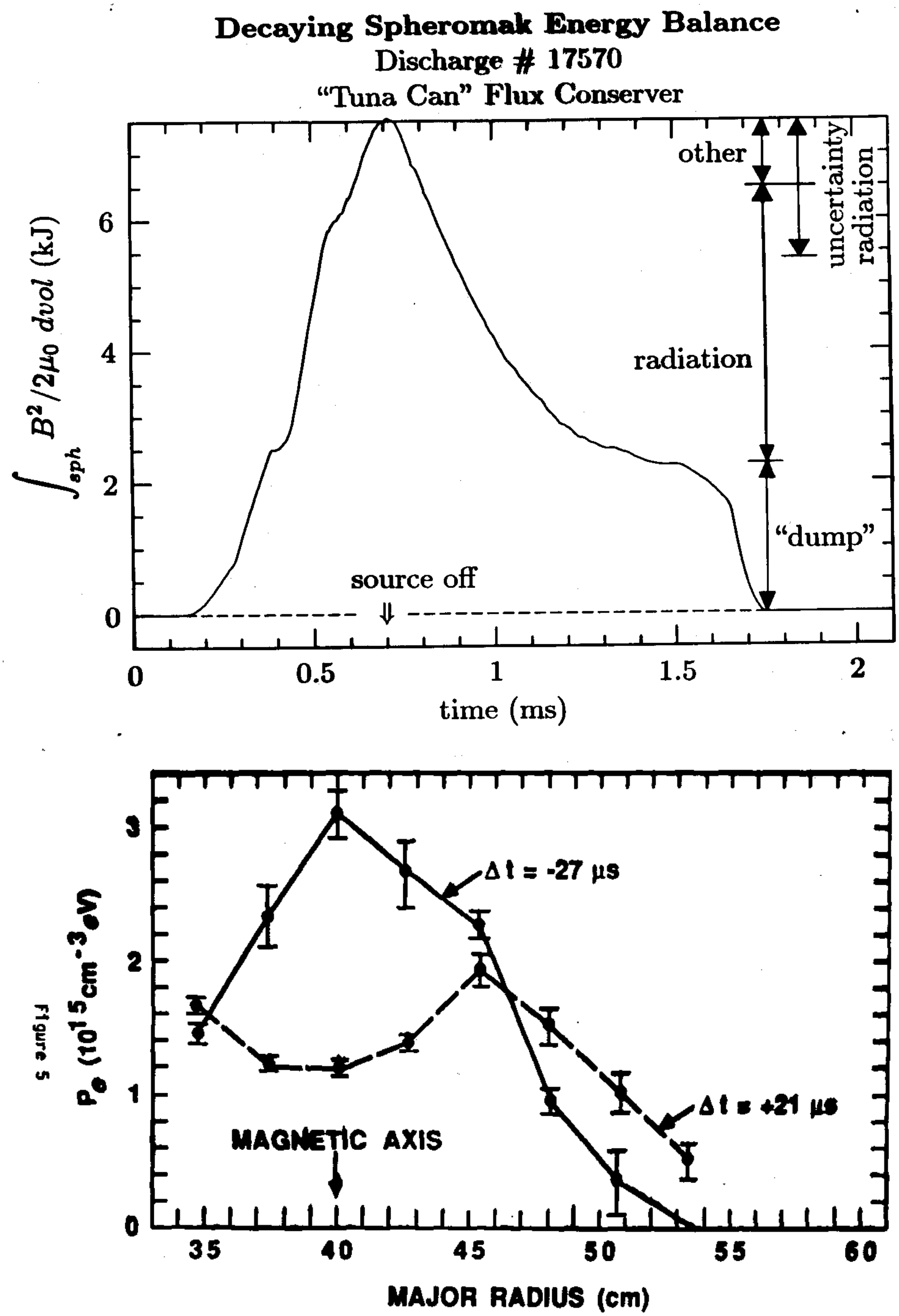
Signature of the pressure-driven instability (determined by 8-beam CO_2 interferometer)

•) Loss of central density (at 1.45 ms).

•) Electron density profile going from peaked to hollow in 10-20 μs.







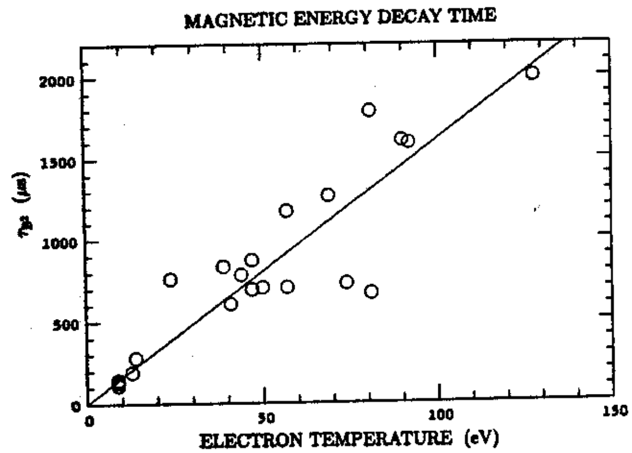
Decaying Spheromak Energy Balance
Discharge # 17570
"Tuna Can" Flux Conserver
$\int_{sph} B^2/2\mu_0 \, dvol$ (kJ)
time (ms)
source off
other
uncertainty
radiation
radiation
"dump"
P_e (10^{15}cm^{-3}eV)
MAJOR RADIUS (cm)
Δt = -27 μs
Δt = +21 μs
MAGNETIC AXIS

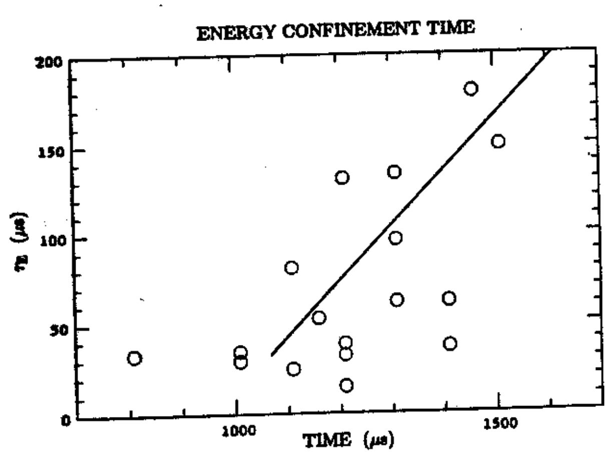
Figure 5

These data show the improved confinement properties obtained in CTX by changing from a mesh to a solid flux conserver with reduced field errors.

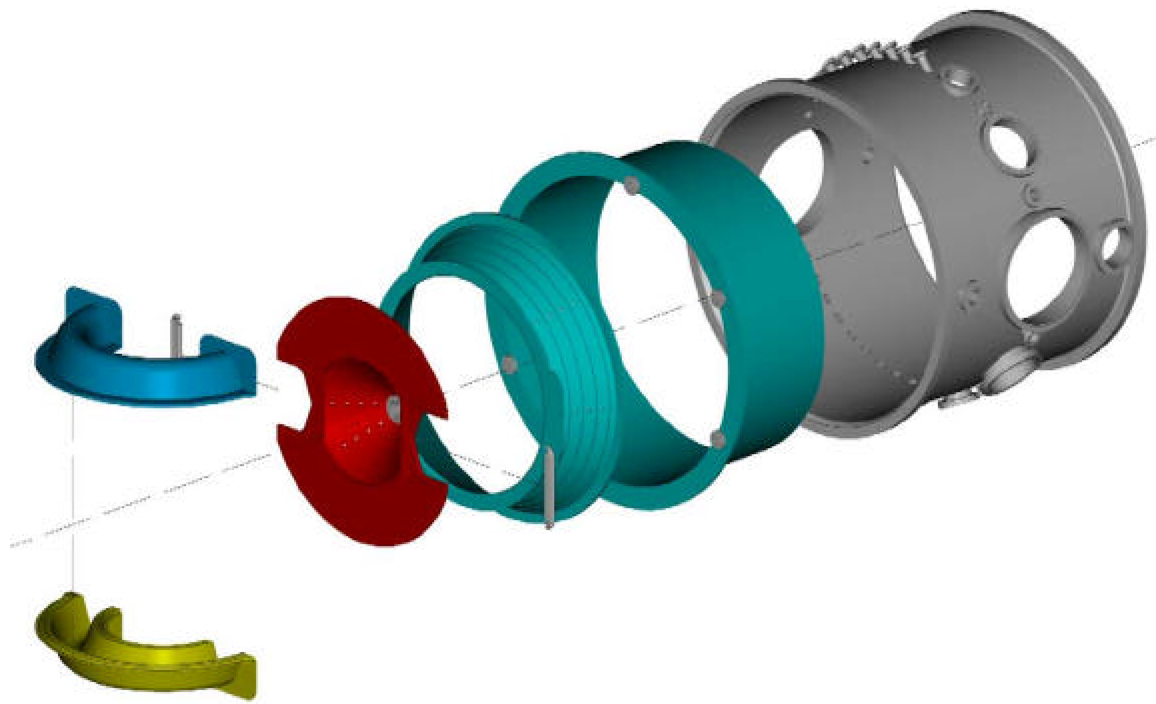
•) Now, the magnetic energy decay time scales with the plasma temperature.

•) The maximum GLOBAL energy confinement time $(3/2\langle\beta\rangle_{\mathrm{vol}}\tau_{B^2})$ has increased to $\approx$ 180 μs.

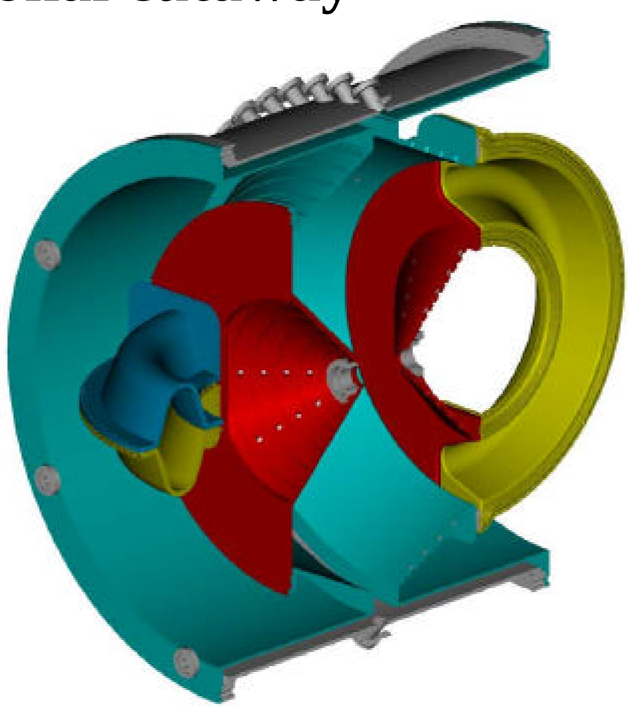




Assembly of HIT-SI

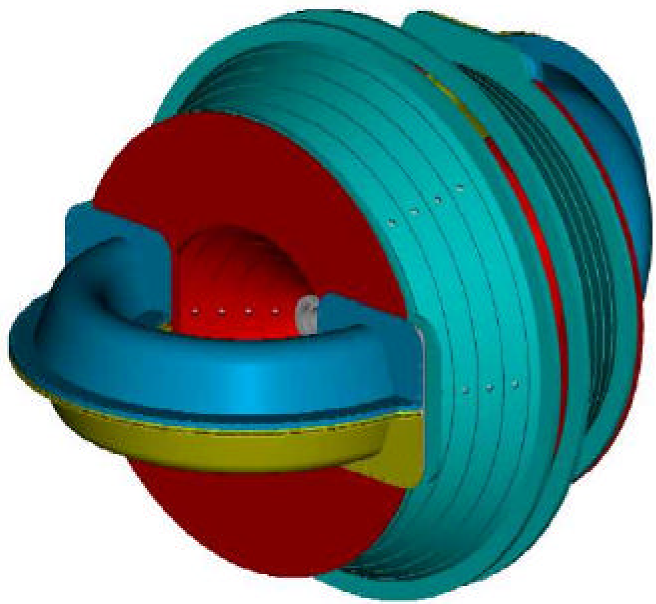


Cross-sectional cutaway



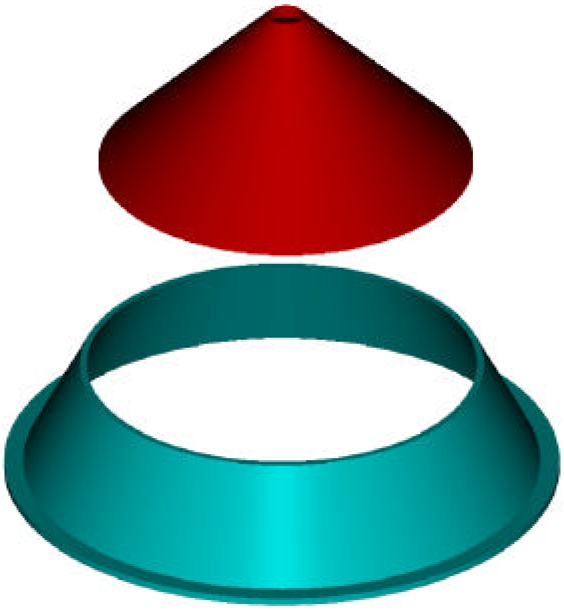
Insulation Requirements

The picture below shows the flux conserving shell of the HIT-SI device. All the pieces shown must be electrically insulated from each other. The table names the time-variant magnetic flux responsible for each insulating break.



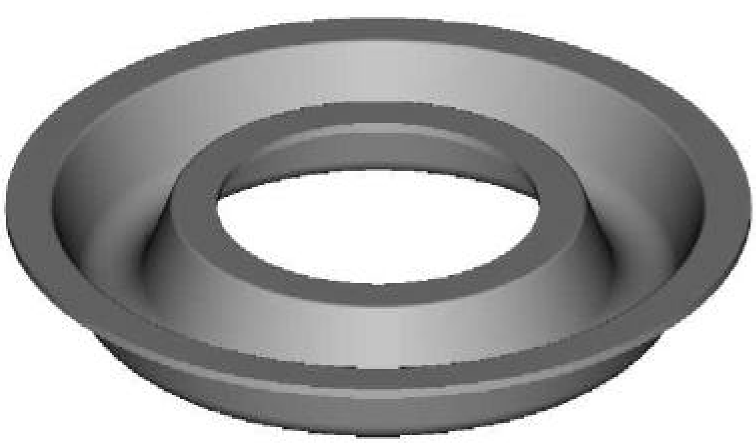
Between…	Upper Injector	Lower Injector	Inner Cone	Outer Cone
Upper Injector		Injector Flux	Transformer Flux	Transformer Flux
Lower Injector	Injector Flux		Transformer Flux	Transformer Flux
Inner Cone	Transformer Flux	Transformer Flux		Injector Flux
Outer Cone	Transformer Flux	Transformer Flux	Injector Flux	

Forming



The inner cone (red piece, left) and the outer cone (light blue frustrum, shown at a smaller scale) will be spun from flat plates of chromium copper.

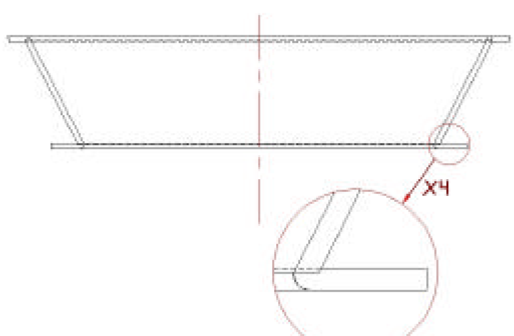
The injectors can also be spun from plate. Two injector halves can be spun as a single piece then cut apart.



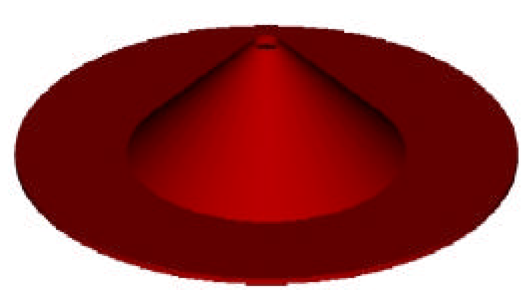
Electron Beam Welding

Electron beam welding (EBW) will be used to join parts when brazing is not feasible. In EBW, a high-energy electron beam is used to quickly melt the base metal in a small area surrounding the joint. EBW was chosen over other welding methods for its performance on high thermal conductivity metals. EBW is used as little as possible in this design because the welding process is highly sensitive to impurities in the C18200 alloy.

EB Welded joints in HIT-SI:



Joining a flange to the outer cone



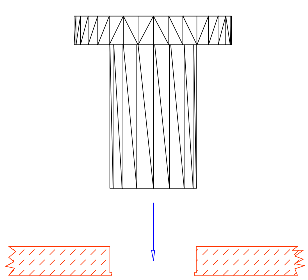
Joining the small cone to a flat plate

Brazing

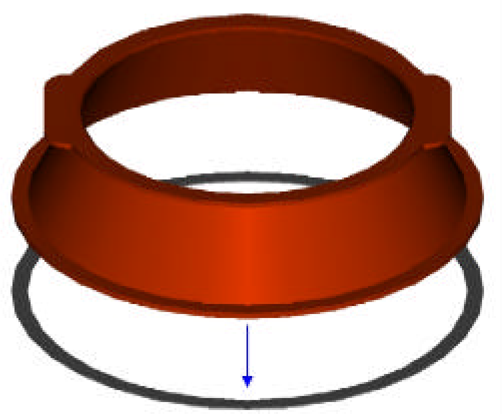
Brazing is the most efficient means of joining Stainless Steel to copper. A gold braze (Bau-4 Au+Ni eutectic) was chosen because the recommended brazing temperature is near the solution treating temperature of Chromium Copper. Combining the brazing and heat treating operations results in:

- Significant cost savings
- Fewer thermal cycles on the material

Brazed joints in HIT-SI:



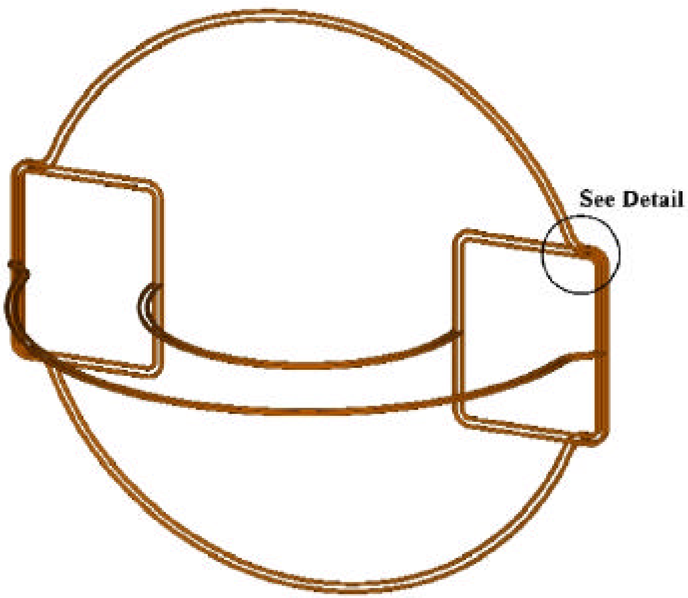
Conflat



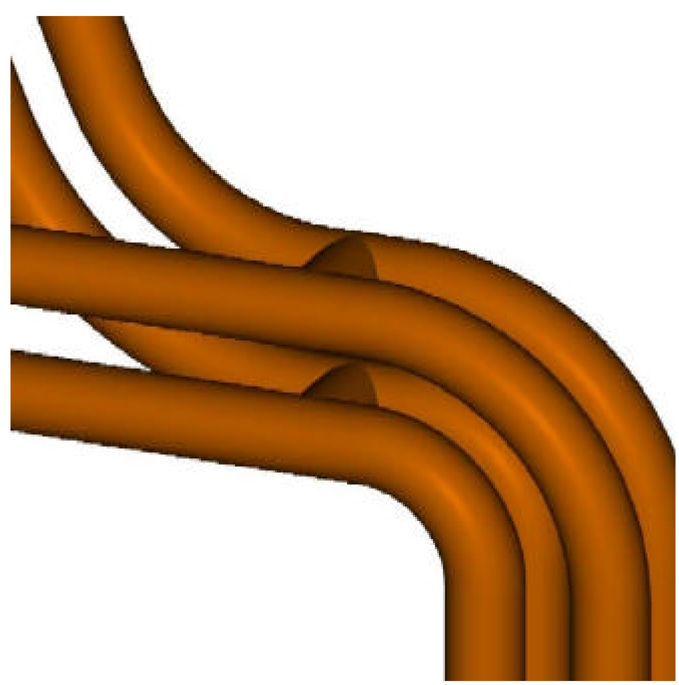
Diagnostic Gap Ring

O-Ring Design

One o-ring lies completely inside the other so that the o-rings don't intersect. Pumping between a double o-ring seal gives a better vacuum than a single o-ring.

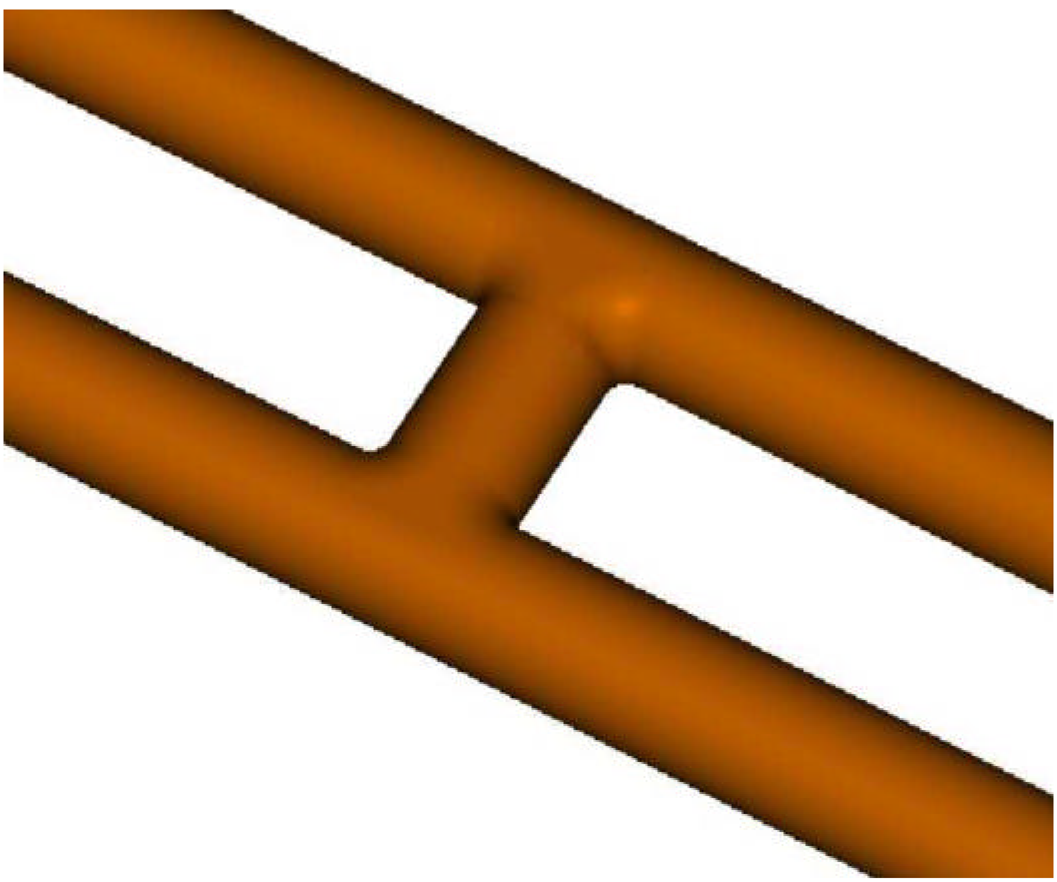


- ***Joint Detail***



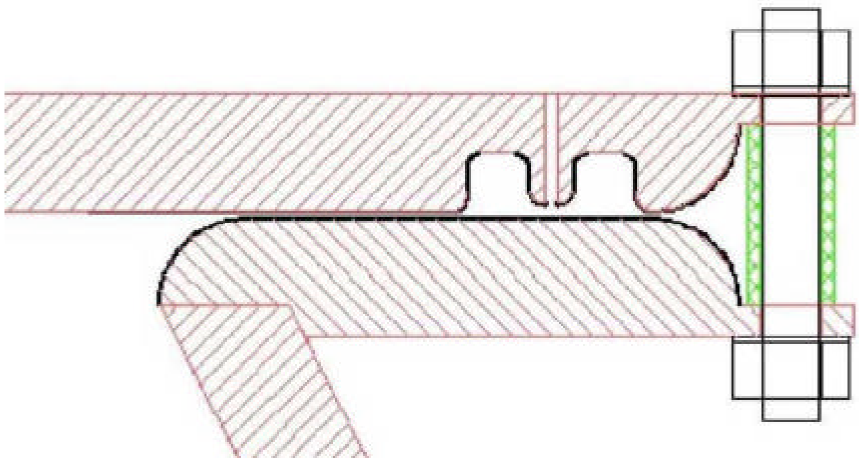
O-Ring Joint

The complicated sealing geometry of HIT-SI makes it necessary to bring o-ring sections together in a tee. One of the molded o-ring joints for HIT-SI is shown below. A solid molded tee is less likely to fail than a tee made from glued circular stock. Also, the corners of the joint can be rounded for a more reliable seal.

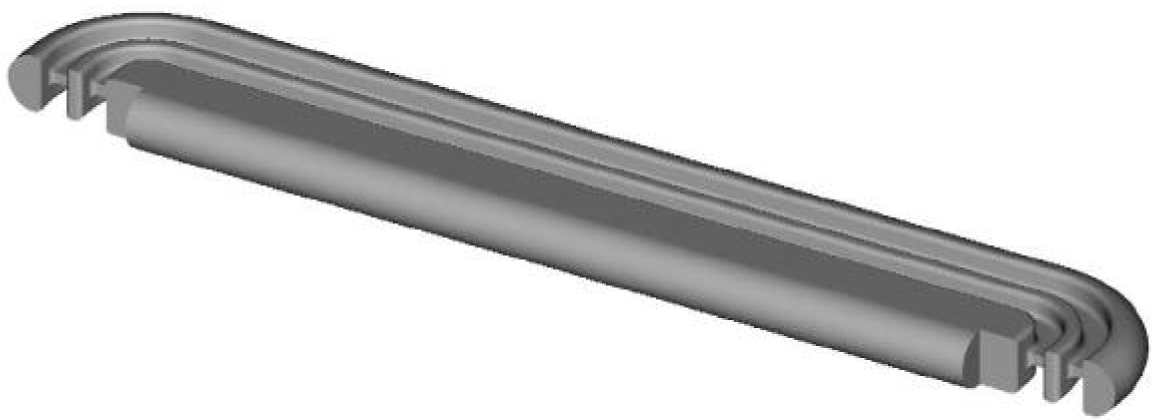


O-Ring Groove Design

- Edges rounded for alumina (Al_2O_3) insulation
- No alumina in bottom of groove
- Notice vacuum port for pumping between O-rings



Alumina Insert



The alumina inserts provide a vacuum seal between the injector and the outer cone flange, as well as guaranteed electrical insulation.

Plasma Sprayed Alumina Insulation

Alumina will be plasma sprayed onto chromium copper surfaces to provide added electrical insulation between sealing surfaces.

Equilibrium-facing surfaces will be masked so that they do not receive an alumina coating. The inside of the injectors will be completely coated with alumina.

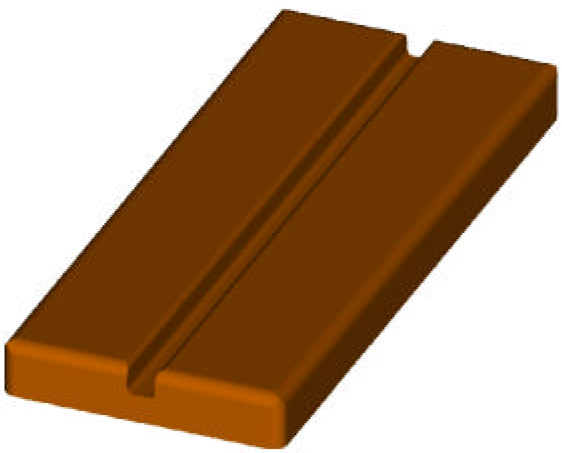
The bottom of the o-ring groove will also remain uncoated to assure a smooth sealing surface.

The sealing surface opposite the o-ring groove will receive a 10-mil alumina coating, and the coating in this area will be lapped and polished into a suitable sealing surface.

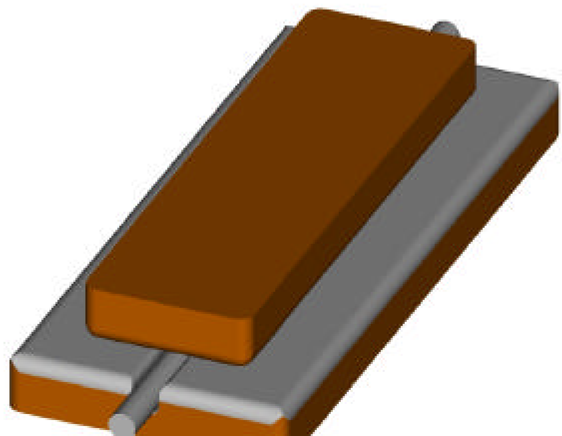
The 10-mil coating has been shown to hold in excess of 4 kV.

Insulation Test

Four test strips were created to evaluate the performance of the alumina coating on the curved surfaces of HIT-SI O-ring grooves. Each groove had different edge radii, width, and depth.



Uncoated test strip

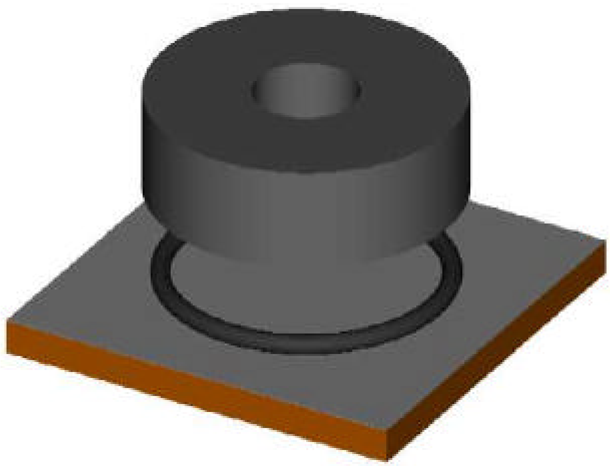


Test set-up

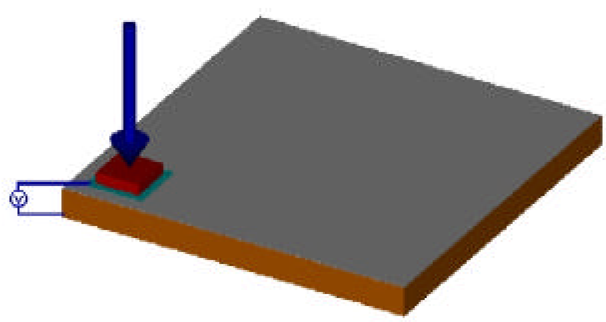
Despite the varying groove geometry, the breakdown potential was approximately 1.7 kV in each case.

Flat Plate Test

Multiple copper plates were sprayed with different spray compositions. Tests are underway to find the coating with the optimal properties.



Vacuum Test



Voltage Test

A successful vacuum test requires a low surface porosity, whereas the voltage test requires low through-thickness porosity.

O-Ring Test Fixture

The O-Ring Test Fixture has provided:

- Experience with the EB welding, brazing, aging, and machining of C18200.
- A platform for evaluating the vacuum quality achievable with an O-ring tee
- A functionally equivalent O-ring groove geometry for testing the electrical insulation provided by the alumina coating